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NEW EXTINCTION AND MASS ESTIMATES OF THE LOW-MASS COMPANION 1RXS 1609 B WITH THE MAGELLAN AO SYSTEM: EVIDENCE OF AN INCLINED DUST DISK*†

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ABSTRACT

We used the Magellan adaptive optics system to image the 11 Myr substellar companion 1RXS 1609 B at the bluest wavelengths to date (z' and Y_s). Comparison with synthetic spectra yields a higher temperature than previous studies of $T_{\rm eff} = 2000 \pm 100$ K and significant dust extinction of $A_V = 4.5^{+0.5}_{-0.7}$ mag. Mass estimates based on the DUSTY tracks gives 0.012–0.015 $M_\odot$, making the companion likely a low-mass brown dwarf surrounded by a dusty disk. Our study suggests that 1RXS 1609 B is one of the ~25% of Upper Scorpius low-mass members harboring disks, and it may have formed like a star and not a planet out at ~320 AU.

Keywords: brown dwarfs — instrumentation: adaptive optics — planetary systems — planets and satellites: individual (1RXS J160929.1–210524 B) — stars: individual (1RXS J160929.1–210524) — stars: pre-main sequence

1. INTRODUCTION

Discovery of substellar companions at hundreds of AU from their host stars in direct imaging surveys has posed challenges to classical formation mechanisms like core accretion (Pollack et al. 1996) and disk instability (Boss 1997). The ultra-wide separations make the core-growing timescale exceedingly long, and observers have not yet discovered such long-lived protoplanetary disks. Some alternatives have been proposed, including gravitational scattering to the current location (Veras et al. 2009) and in situ star-like formation.

Detecting and characterizing circumsubstellar disks can place constraints on formation mechanisms. Many substellar (close to planetary mass) companions have been suggested to host their own disks (separate from the primary's disk) based on O/IR emission lines or excess. The 1.28 μm Pa β emission line was seen on GQ Lup B (Seifahrt et al. 2007), CT Cha B (Schmidt et al. 2008), GSC 06214–00210 B (Bowler et al. 2011), and FW Tau C (Bowler et al. 2014). *Hubble Space Telescope* observations by Zhou et al. (2014) also showed that GSC 06214–00210 B, GQ Lup B, and DH Tau B exhibit an optical excess at ~0.3–0.7 μm, implying a mass accretion rate of 10^{-11}–10^{-9} $M_\odot$ yr^{-1}. Kraus et al. (2014) also found that 1RXS 1609 B, GQ Lup B, GSC 06214–00210 B, DH Tau B, and ROXs 12 B have redder $K' - L'$ colors than young field dwarfs. An unresolved 24 μm excess was also detected on GSC 06214–00210 B and 1RXS 1609 B (Bailey et al. 2013). In particular, Kraus et al. (2015) presented an ALMA Cycle 1 1.3 mm detection of dust continuum emission associated with FW Tau C and derived a dust mass of 1–2 $M_\oplus$. Caceres et al. (2015) further detected CO (2–1) and showed that gas is also present in this disk. Although FW Tau C could be in the brown dwarf regime ($M \sim 10 \pm 4$ $M_{\rm jup}$; Kraus et al. 2014), these observations may represent the first direct detection of a disk around a planetary mass object.

Recently, using the 6.5m Magellan adaptive optics system (MagAO; Close et al. 2013; Males et al. 2014) we have also detected an r' (0.63 μm) excess possibly due to Hα and a dust extinction of $A_V = 3$–4 mag for CT Cha B (Wu et al. 2015). All of these observations suggest that circumsubstellar disks could be common around these wide young planetary mass objects. The existence of disks also favors star-like fragmentation, but argues against a scattering origin. This is because disks may be perturbed, if not destroyed, by each encounter with another massive body (Bowler et al. 2011; Bailey et al. 2013).

Here we present MagAO z' and Y_s imaging of 1RXS 1609 B, a substellar companion discovered at 320 AU (projected separation) from 1RXS J160929.1–210524 in the Upper Scorpius association by Lafrenière et al. (2008). The companion is widely reported as the first directly imaged exoplanet orbiting a Sun-like star. Its mass, temperature, and spectral type were determined to be 0.008–0.011 $M_\odot$, ~1800 K, and ~L4 (Lafrenière et al. 2008, 2010; Lachapelle et al. 2015). Recently, Pecaut et al. (2012) revised the age for Upper Sco to be 11 ± 2 Myr, and, based on that, they derived a higher mass 14^{+2}_{-3} $M_{\rm jup}$. In this paper, we show that 1RXS 1609 B may have some dust extinction, a higher temperature, and an earlier spectral type. Therefore, it is more likely a low-mass brown dwarf slightly obscured

* As argued by Pecaut et al. (2012), GSC 06213–03158 B or [PZ99] J160930.3–210459 B might be better names.

† This paper includes data gathered with the 6.5 m Magellan Clay Telescope at Las Campanas Observatory, Chile.

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by a dusty circumsecondary disk.

2. OBSERVATIONS AND REDUCTION

We used MagAO, a new AO system on the 6.5 m Clay Telescope, to image 1RXS 1609 A and B at z' ($\lambda = 0.91$ μm; $\Delta\lambda = 0.12$ μm) and Y_s ($\lambda = 0.98$ μm; $\Delta\lambda = 0.09$ μm) on 2013 April 6 (UT) during the second commissioning run. Seeing varied between 0.″6 and 0.″8. We used the primary ($R \sim 12.4$ mag) as the guide star, and locked the AO system at 100 Karhunen–Loève modes and 400 Hz. This is a very faint target given that 50% of the light goes to the VisAO science camera and 50% to the pyramid wavefront sensor. That is why only 100 of 378 possible modes were corrected at 400 Hz compared to the usual 1000 Hz loop speed. The resulting FWHMs were 67 and 72 mas for z' and Y_s, respectively. For z', we obtained 20 s × 193 (3860 s) and 2.27 s × 28 (63.6 s) for saturated and unsaturated data, respectively. For Y_s, we obtained 20 s × 126 (2520 s) unsaturated frames. We only detected 1RXS 1609 B at z' but not Y_s, possibly due to a lower quantum efficiency which leads to a lower total throughput (0.013 versus 0.077). To calibrate our photometry, we retrieved K7V, M0V, and M1V spectral templates from the Pickles Atlas (Pickles 1998), reddened them by $A_V = 0.1$ mag (extinction of A; Bowler et al. 2014), and integrated the DENIS (Epchtein et al. 1997) I and our z' and Y_s filter curves over these templates as well as the Vega spectrum to derive $I - z'$ and $I - Y_s$ colors. Then we applied these colors to the existing DENIS I measurement on the primary to obtain z' and Y_s photometry. We adopted 0.06 and 0.10 mag as the uncertainties for z' and Y_s based on comparison to F7V and M1V templates. We also observed the optical standard star LTT 3864 in the same observing run, but difficulties in dealing with Strehl ratio variation on different nights and the inherent noisiness of large aperture CCD photometry made calibrations much less precise than using the DENIS photometry. However, we found consistent results to within 10% for the photometry for 1RXS 1609 A. This demonstrated that the primary is not a very active variable and that the DENIS I band photometry is valid for the night of 2013 April 6.

In the following analysis on the z' data, we selected frames with wavefront errors less than 175 nm rms, corresponding to the best two-thirds of data (129 frames). Data reduction were as detailed in Wu et al. (2015). We constructed a master point spread function (PSF) from the unsaturated images and performed PSF-fitting photometry. In addition, aperture photometry was done using an aperture of 1 FWHM in radius. Our final z' flux is the average of both approaches, and its uncertainty included a ∼0.1 mag offset between them. To estimate any possible flux loss in halo subtraction, we subtracted scaled-down PSFs at the position of the companion (negative PSF injection) without removing the halo and found a consistent $\Delta z'$ with our aperture and PSF-fitting photometry. Therefore, we concluded that there was no significant flux loss when removing the radially symmetric PSF halo profile. The astrometric error budget also included image distortion (Wu et al. 2015). Table 1 summarizes the system properties.

Table 1
Properties of 1RXS 1609 System

Property	Primary		Companion
Distance (pc)[a,b]		145 ± 14	
Separation (″)[c]		2.21 ± 0.01	
PA (°)[c]		27.1 ± 0.3	
Age (Myr)[d]		11 ± 2	
Spectral type	M0 $\pm$ 1[e]		L2 $\pm$ 1[c]
$T_{\rm eff}$ (K)	4060^{+300}_{-200} [f]		2000 ± 100 [c]
A_V (mag)	$0.1^{+0.3}_{-0.1}$ [e]		$4.5^{+0.5}_{-0.7}$ [c]
$\log(L_{\rm bol}/L_\odot)$	-0.37 ± 0.15 [f]		-3.36 ± 0.09 [c]
Mass ($M_\odot$)	$0.85^{+0.20}_{-0.10}$ [f]		0.012–0.015[c]
I[g]	10.99 ± 0.03		...
z'[c]	10.60 ± 0.06		21.24 ± 0.15
Y_s[c]	10.43 ± 0.10		>19.46 (3σ)
J[h,i]	9.764 ± 0.027		17.85 ± 0.12
H[h,i]	9.109 ± 0.023		16.86 ± 0.07
K_s[h,i]	8.891 ± 0.021		16.15 ± 0.05
3.1 μm[j]	8.80 ± 0.05		15.65 ± 0.21
3.3 μm[j]	8.78 ± 0.05		15.20 ± 0.16
L'[k]	8.73 ± 0.05		14.8 ± 0.3
24 μm (mJy)[j]		3.06 ± 0.04	

Note. — [a] de Zeeuw et al. (1999). [b] Ireland et al. (2011). [c] This work. [d] Pecaut et al. (2012). [e] Bowler et al. (2014). [f] Lafrenière et al. (2008). [g] DENIS (Epchtein et al. 1997). [h] 2MASS (Skrutskie et al. 2006). [i] Lachapelle et al. (2015). [j] Bailey et al. (2013). [k] Lafrenière et al. (2010).

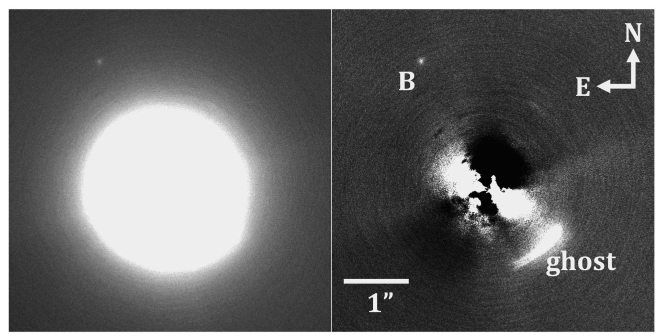

Figure 1. Left: 1RXS 1609 in MagAO z' filter. Right: after subtracting the radially symmetric profile of the primary star.

3. RESULTS

3.1. *Properties of the Companion*

3.1.1. *Temperature and Extinction*

Figure 1 shows MagAO z' images of the system. We find a contrast of $\Delta z' = 10.64 \pm 0.14$ mag between components. In Figure 2, we compare our z' and Y_s measurements, together with the published JHK_s spectra and photometry (Lafrenière et al. 2008, 2010; Lachapelle et al. 2015), to the 1800 K Phoenix-ACES (Barman et al. 2011a, 2011b), AMES-Dusty (Allard et al. 2001), and four Lγ dwarfs[8] in Allers & Liu (2013): 2MASS J05184616–2756457 (L1γ), 2MASS J05361998–1920396 (L2γ), 2MASS J22081363+2921215 (L3γ), and 2MASS J05012406–0010452 (L4γ). While the models and these Lγ spectra fit 1RXS 1609 B reasonably well in the near-infrared, they all seem to be too bright at z' by a factor of ∼2–4, suggesting that some dust might be present to redden the companion. There-

[8] Cruz et al. (2009) proposed a classification scheme of γ and β for ∼10 Myr (low surface gravity) and ∼100 Myr (intermediate surface gravity) dwarfs, respectively.

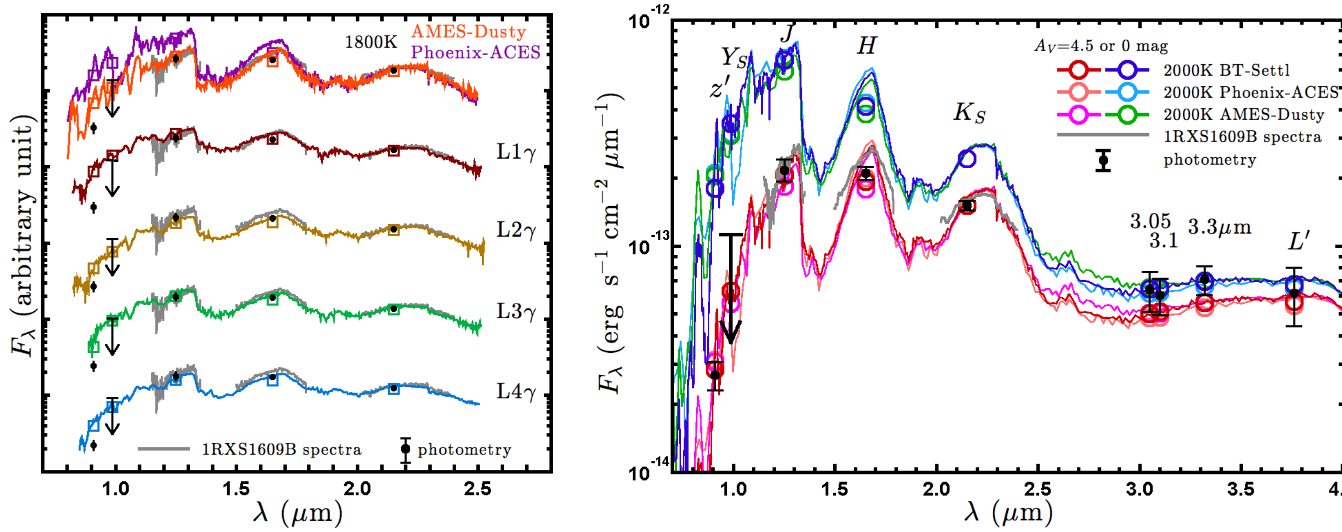

Figure 2. Left: we compare the photometry and spectra of 1RXS 1609 B (Lafrenière et al. 2008, 2010) to the 1800 K AMES-Dusty and Phoenix-ACES models ($A_V = 0$ mag) and four low-surface gravity Lγ dwarfs in Allers & Liu (2013). We normalize them at K_s. Squares represent synthetic fluxes at $z'Y_sJHK_s$, and the Y_s (0.98 μm) arrow extends from 3σ down to 1σ. The companion's z' flux is lower than that of Lγ dwarfs and the models as well, suggesting that some dust extinction might be needed. We also note that these Lγ objects may themselves also be reddened by dust; for example, the L2γ appears redder than the L3 and L4 counterparts.
Right: SED fitting with the 2000 K models. The blue curves represent what the object's spectra would be if there was no extinction. Circles denote model fluxes for filters. The Y_s arrow extends from 3σ down to 1σ. We need a high extinction $A_V \sim 4.5$ mag (red curves) to match our observed Y_s upper limit and z' flux. Note that a weak ($\sim$20%) $\sim$3 μm excess becomes apparent when the extincted SEDs are compared to the observations (3.05, 3.1, and 3.3 μm data points are slightly above the red curves).

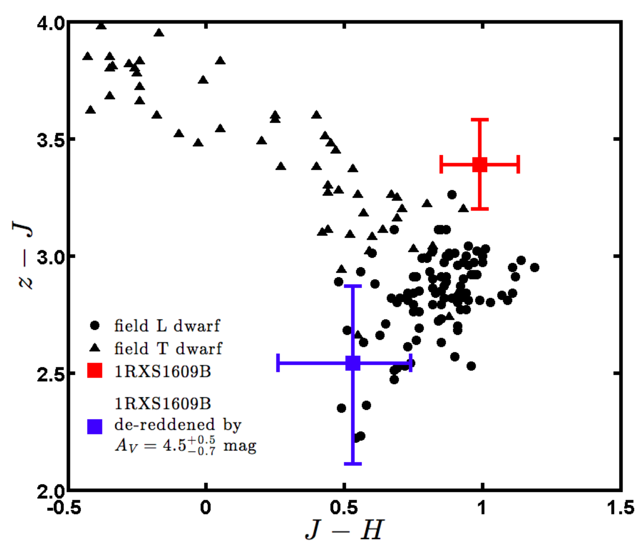

Figure 3. $z - J$ vs. $J - H$ of 1RXS 1609 B and field L, T dwarfs (Golimowski et al. 2004; Knapp et al. 2004; Chiu et al. 2006). Once de-reddened by $A_V \sim 4.5$ mag, the color of 1RXS 1609 B is similar to that of L dwarfs.

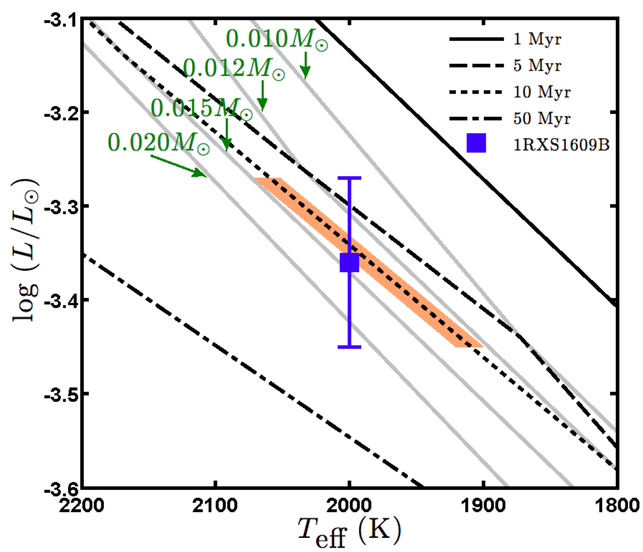

Figure 4. H–R diagram with DUSTY evolutionary tracks. Iso-mass curves are shown in gray. The salmon colored polygon is the only region consistent with the observed $T_{\rm eff} = 1900$–2100 K, $\log(L_{\rm bol}/L_\odot) = -3.36 \pm 0.09$, and the age of Upper Sco (11 ± 2 Myr). This yields a mass estimate of 0.012–0.015 $M_\odot$.

fore, in this study we explore other possibilities. We carry out a spectral energy distribution (SED) fitting using three atmospheric models: Phoenix-ACES, AMES-Dusty, and BT-Settl (Allard et al. 2011). We adopt log $g = 4.0$ from previous analyses (Lafrenière et al. 2008, 2010; Lachapelle et al. 2015). Then we apply the extinction law in Weingartner & Draine (2001) and Draine (2003) to redden these synthetic spectra. As in Wu et al. (2015), to evaluate the goodness of fit, we match these reddened models with the observed K_s flux because the K band is most likely dominated by photospheric emission and least affected by dust emission and extinction. In general, we find that the reddened Phoenix-ACES synthetic spectra give the best fit, followed by the BT-Settl and AMES-Dusty models. Chi-square analysis gives $T_{\rm eff} = 2000 \pm 100$K, slightly higher than previous estimates. Extinction is more model dependent due to different treatments of opacity, varying from $A_V = 2.7$ to 5.3 mag at this temperature range, so we compute a weighted average and adopt $A_V = 4.5^{+0.5}_{-0.7}$ mag.

Figure 2 also shows our SED fitting with models added $A_V = 0$ and 4.5 mag. We note that these fluxes are not absolute in order to avoid the $\sim$10% distance uncertainty. We also normalize the companion's JHK_s spectra (gray curves) to their apparent fluxes. The red curves are nor-

malized at the apparent K_s flux, while the blue curves represent the object's true SED when extinction is not present. Overall these reddened models fit the photometry and spectra reasonably well. The 3σ Y_s upper limit also suggests that 1RXS 1609 B is likely obscured, otherwise we would have detected it.

We also notice that the system has an unresolved 24 μm excess of 0.91 mJy (Bailey et al. 2013). Since the primary star has very little extinction, $A_V \sim 0.1$ mag (Bowler et al. 2014), it is possible that most of this warm dust excess originates from the companion. As mentioned in the Introduction, Kraus et al. (2014) found that 1RXS 1609 B and a few other objects exhibit $K'-L'$ excess, which indicates that disks may be common to young substellar companions. In Figure 2 there is evidence ($<2\ \sigma$) of a weak $\sim$20% 3–4 μm excess compared with our best-fit SEDs. In addition, in Figure 3 we find that 1RXS 1609 B has $z - J$ redder than field L dwarfs (e.g., Golimowski et al. 2004; Knapp et al. 2004; Chiu et al. 2006). Finally, the SED appears to need pure ISM-like reddening ($A_V \sim 4.5$ mag), in contrast to the gray extinction usually invoked in atmospheric planetary models with thick clouds (e.g., HR 8799 b, Barman et al. 2011a; 2M 1207 b, Skemer et al. 2011; Barman et al. 2011b). All of these lines of evidence seem to suggest that 1RXS 1609 B hosts its own inclined dust disk. Really, this is not a surprising result given that $\sim$25% of low-mass objects in Upper Sco have dusty disks (Luhman & Mamajek 2012) and 1RXS 1609 B was the faintest, reddest object found by the discoverers' AO survey of Upper Sco (Lafrenière et al. 2014), so the odds are good that the faintest, reddest object might also have dust extinction as well—making 1RXS 1609 B appear redder and fainter than its intrinsic true color and luminosity.

3.1.2. *Spectral Type, Luminosity, Mass, and Radius*

We calculate four gravity-insensitive indices H_2O, H_2OD, H_2O-1, and H_2O-2 as defined in Allers & Liu (2013). The average of these indices shows $\sim$L2 for A_V between 3 and 6 mag, earlier than previous estimates of L4 $\pm$ 1 (Lafrenière et al. 2008, 2010; Lachapelle et al. 2015). Our result is also in agreement with the recent analysis by Manjavacas et al. (2014), who fit an L2γ spectra to that of 1RXS 1609 B. Therefore, we adopt L2 $\pm$ 1.

With $A_V = 4.5^{+0.5}_{-0.7}$ mag and $D = 145 \pm 14$ pc, we calculate $\log(L_{\rm bol}/L_\odot) = -3.36 \pm 0.09$ using the bolometric correction in Schmidt et al. (2014). To validate, we integrate the de-reddened spectra in Figure 2 and obtain ~ -3.32, suggesting that the bolometric correction derived from field dwarfs works reasonably well for young objects. Compared to the DUSTY evolutionary tracks (Chabrier et al. 2000; see Figure 4), the companion has a mass between 0.012 and 0.015 $M_\odot$, consistent with Pecaut et al. (2012) but higher than 0.008–0.011 $M_\odot$ found in other studies. Therefore, we suggest that 1RXS 1609 B likely lies above the fiducial brown dwarf/planet boundary.

Finally, we obtain $\sim$1.7 Jupiter radii using the new luminosity and temperature, consistent with the DUSTY tracks.

3.2. *Implications*

If 1RXS 1609 B harbors an inclined disk, this will imply that circumsubstellar disks could survive after 10 Myr. This is not entirely unexpected because the recent large infrared survey in the Upper Sco revealed longer disk lifetimes for low-mass stars (Luhman & Mamajek 2012). The survival of disks also supports in situ fragmentation for companions on wide orbits and disfavors the planet–planet scattering scenario. Since no accretion-indicating lines were detected in the NIR spectrum, ongoing accretion is either slow or non-existent. The putative disk may be largely gas depleted, precluding accretion, while still retaining sufficient dust mass at larger radii to produce the observed extinction. Future ALMA observations could definitively test the existence of this disk.

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